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We present joint constraints on the number of effective neutrino species $N_{\rm eff}$ and the sum of neutrino masses $\sum m_\nu$, based on a technique which exploits the full information contained in the one-dimensional Lyman-α forest flux power spectrum, complemented by additional cosmological probes. In particular, we obtain $N_{\rm eff} = 2.91^{+0.21}_{-0.22}$ (95% CL) and $\sum m_\nu < 0.15$ eV (95% CL) when we combine BOSS Lyman-α forest data with CMB (Planck+ACT+SPT+WMAP polarization) measurements, and $N_{\rm eff} = 2.88 \pm 0.20$ (95% CL) and $\sum m_\nu < 0.14$ eV (95% CL) when we further add baryon acoustic oscillations. Our results tend to favor the normal hierarchy scenario for the masses of the active neutrino species, provide evidence for the Cosmic Neutrino Background from $N_{\rm eff} \sim 3$ ($N_{\rm eff} = 0$ is rejected at more than 14 σ), and rule out the possibility of a sterile neutrino thermalized with active neutrinos (i.e., $N_{\rm eff} = 4$) – or more generally any decoupled relativistic relic with $\Delta N_{\rm eff} \simeq 1$ – at a significance of over 5 σ, the strongest bound to date, implying that there is no need for exotic neutrino physics in the concordance ΛCDM model.

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The Standard Model of particle physics predicts that there are exactly three active neutrinos, one for each of the three charged leptons, and that neutrinos are all left-handed and with zero mass [1]. However, from experimental results on solar and atmospheric neutrino oscillations we now know that neutrinos are massive, with at least two species being non-relativistic today [2, 3]. The distinctness of the three flavors, and the difference between neutrinos and antineutrinos depend critically on the condition of being massless. Therefore, the discovery that neutrinos have non-zero mass calls also into question the number of neutrino species. All these issues have triggered an intense research activity in neutrino science over the last few years, with a remarkable interplay and synergy between cosmology and particle physics. The measurement of the absolute neutrino mass scale remains the greatest challenge for both disciplines. However, while particle physics experiments are capable of determining two of the squared mass differences, along with the number of active neutrino families, their mixing angles, and one of the complex phases [4], a combination of cosmological state-of-the-art datasets allows one to place more competitive upper limits on the total neutrino mass (summed over the three families) as opposed to beta-decay experiments – leading to the strongest upper bound to date [5]. Knowledge of the total mass and type of hierarchy will complete the understanding of the neutrino sector, and shed light into several critical issues in particle physics – such as leptogenesis or baryogenesis.

Cosmological measurements are also capable of constraining the properties of relic neutrinos, and possibly of other light relic particles. In particular, the density of radiation $\rho_{\rm R}$ in the Universe (which includes photons and additional species) is usually parameterized by the effective number of neutrino species $N_{\rm eff}$, and the neutrino contribution to the total radiation content is expressed in terms of $N_{\rm eff}$ via the relation

$$\rho_{\rm R} = \rho_\gamma + \rho_\nu = \Big[1 + \frac{7}{8}\Big(\frac{4}{11}\Big)^{4/3} N_{\rm eff}\Big]\rho_\gamma, \qquad (1)$$

where ρ_γ and ρ_ν are the energy density of photons and neutrinos, respectively [2]. This relation is valid when neutrino decoupling is complete, and holds as long as all neutrinos are relativistic. In the Standard Model, $N_{\rm eff} = 3.046$ due to non instantaneous decoupling corrections, and therefore any departure from this value would indicate non-standard neutrino features or an extra contribution from other relativistic relics. Recently, there has been some mild preference for $N_{\rm eff} > 3.046$ from cosmic microwave background (CMB) anisotropy measurements [6–8]: an excess from the expected standard number could be produced by sterile neutrinos, a neutrino/anti-neutrino asymmetry or any other light relics in the Universe. Constraints from Planck (2013) data in scenarios where the extra relativistic degrees of freedom are either massless or massive tend to disfavor $N_{\rm eff} = 4$, but only at the $\sim 2\ \sigma$ level (except when data on direct H_0 measurements are included), leaving still room for dark radiation [9].

In this Letter, we present a method to obtain join constraints on $N_{\rm eff}$ and the total neutrino mass $\sum m_\nu$ using the information contained in the one-dimensional Lyman-α (Lyα) forest flux power spectrum, complemented by other cosmological probes. In particular, we show how this technique is able to rule out the presence of an additional sterile neutrino thermalized with three active neutrinos (i.e., $N_{\rm eff} = 4$) – or more generally any dark radiation – at a significance of over 5 σ, and provide strong evidence (greater than 14 σ) for the Cosmic Neutrino Background (CNB) from $N_{\rm eff}\sim 3$. Hence, our results have important implications in cosmology and particle physics, especially suggesting that there is no indication for extra relativistic degrees of freedom, and that the minimal ΛCDM model does not need to be extended further to accommodate non-standard dark radiation.

Datasets – The joint constraints on $N_{\rm eff}$ and $\sum m_\nu$ presented in this work are obtained from a combination of large-scale structure (LSS) and CMB measurements. As LSS probes, we used the one-dimensional Lyα forest flux power spectrum derived from the Data Release 9 (DR9) of the Baryon Acoustic Spectroscopic Survey (BOSS) quasar data [10], combined with the measurement of the Baryon Acoustic Oscillation (BAO) scale in the clustering of galaxies from the BOSS Data Release 11 (DR11) [11]. BOSS [12] is the cosmological counterpart of the third generation of the Sloan Digital Sky Survey (SDSS), the leading ground-based astronomical survey designed to explore the large-scale distribution of galaxies and quasars by using a dedicated 2.5m telescope at Apache Point Observatory [13]. Specifically for the Lyα forest, our data consist of 13 821 quasar spectra, carefully selected according to their high quality, signal-to-noise ratio and spectral resolution, to bring systematic uncertainties at the same level of the statistical uncertainties. The Lyα forest flux power spectrum is measured in twelve redshifts bins, from $\langle z\rangle = 2.2$ to 4.4, in intervals of $\Delta z = 0.2$, and spans thirty-five wave numbers in the k range $[0.001 - 0.02]$, with k expressed in $({\rm km/s})^{-1}$. Correlations between different redshift bins were neglected, and the Lyα forest region was divided into up to three distinct z-sectors to minimize their impact. Noise, spectrograph resolution, metal contaminations and other systematic uncertainties were carefully subtracted out or accounted for in the modeling. As CMB probes, we adopted a combination of datasets collectively termed 'CMB', which includes Planck (2013) temperature data from the March 2013 public release (both high-ℓ and low-ℓ) [14], the high-ℓ public likelihoods from the Atacama Cosmology Telescope (ACT) [15] and the South Pole Telescope (SPT) [16] experiments, and some low-ℓ WMAP polarization data [17].

Methodology – To derive joint constraints on $N_{\rm eff}$ and $\sum m_\nu$ we adopted a procedure similar to the one applied in [5], properly extended by using a simple analytic approximation to include non-standard dark radiation models in the Lyα likelihood. The main goal is to construct a multidimensional likelihood $\mathcal{L}$, which is the product of individual likelihoods defining the various cosmological probes considered (LSS and CMB), i.e., $\mathcal{L}=\mathcal{L}^{\rm LSS}\mathcal{L}^{\rm CMB}=\mathcal{L}^{\rm Ly\alpha}\mathcal{L}^{\rm BAO}\mathcal{L}^{\rm Planck}\mathcal{L}^{\rm ACT}\mathcal{L}^{\rm SPT}\mathcal{L}^{\rm WMAP}$. The global $\mathcal{L}$ is then interpreted in the context of the frequentist or classical confidence level method [18], and its analysis allows one to obtain joint or individual parameter constraints. We approximated $\mathcal{L}^{\rm CMB}$ by a multivariate Gaussian, and assumed the best-fit and covariance matrix directly from the Planck results [9, 14] in the case of a ΛCDM model extended to massive neutrinos and an arbitrary number of massless extra degrees of freedom, while we used the correlation matrix with a posterior based on BAOs from the official Planck (2013) chains to account for $\mathcal{L}^{\rm BAO}$. We then constructed the Lyα forest likelihood with an elaborated procedure briefly described as follows – but see [5, 19, 20] for all the numerical and data-oriented aspects. In more detail, for a model $\mathcal{M}$ defined by three categories of parameters – cosmological ($\boldsymbol{\alpha}$), astrophysical ($\boldsymbol{\beta}$), nuisance ($\boldsymbol{\gamma}$) – globally indicated with the multidimensional vector $\boldsymbol{\Theta}=(\boldsymbol{\alpha},\boldsymbol{\beta},\boldsymbol{\gamma})$, and for a $N_{\rm k}\times N_{\rm z}$ dataset $\boldsymbol{X}$ of power spectra $P(k_{\rm i}, z_{\rm j})$ measured in $N_{\rm k}$ bins in k and $N_{\rm z}$ bins in redshift with experimental Gaussian errors $\sigma_{\rm i,j}$, with $\boldsymbol{\sigma}=\{\sigma_{\rm i,j}\}$, $i=1,N_{\rm k}$ and $j=1,N_{\rm z}$, the Lyα likelihood is written as:

$$\mathcal{L}^{Ly\alpha}(\boldsymbol{X},\boldsymbol{\sigma}|\boldsymbol{\Theta})=\frac{\exp[-(\Delta^{\rm T}C^{-1}\Delta)/2]}{(2\pi)^{\frac{N_{\rm k}N_{\rm z}}{2}}\sqrt{|C|}}\,\mathcal{L}^{Ly\alpha}_{\rm prior}(\boldsymbol{\gamma}) \quad (2)$$

where Δ is a $N_{\rm k}\times N_{\rm z}$ matrix with elements $\Delta(k_{\rm i},z_{\rm j}) = P(k_{\rm i},z_{\rm j})-P^{\rm th}(k_{\rm i},z_{\rm j})$, $P^{\rm th}(k_{\rm i},z_{\rm j})$ is the predicted theoretical value of the power spectrum for the bin $k_{\rm i}$ and redshift $z_{\rm j}$ given the parameters $(\boldsymbol{\alpha},\boldsymbol{\beta})$ and computed from simulations [19], C is the sum of the data and simulation covariance matrices, and $\mathcal{L}^{Ly\alpha}_{\rm prior}(\boldsymbol{\gamma})$ accounts for the nuisance parameters, a subset of the parameters $\boldsymbol{\Theta}$. Specifically, for the baseline model we considered five cosmological parameters $\boldsymbol{\alpha}$ in the context of the ΛCDM paradigm assuming flatness, i.e. $\boldsymbol{\alpha}=(n_{\rm s},\sigma_8,\Omega_{\rm m},H_0,\sum m_\nu)$, four astrophysical parameters $\boldsymbol{\beta}$ related to the state of the intergalactic medium (IGM) – two for the effective optical depth of the gas assuming a power law evolution, and two related to the heating rate of the IGM – and 12 nuisance parameters $\boldsymbol{\gamma}$ to account for imperfections in the measurements and in the modeling, plus two additional parameters for the correlated absorption of Lyα and either Si-III or Si-II. The global theoretical Lyα power spectrum $P^{\rm th}(k_{\rm i},z_{\rm j})$, as a function of $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$, is obtained via a second-order Taylor expansion around a central model chosen to be in agreement with Planck (2013) cosmological results. We devised a novel suite of hydrodynamical cosmological simulations which include massive neutrinos [19] to map the parameter space around the central reference model on a regularly-spaced grid, and used those simulations to compute first and second-order derivatives in the Taylor expansion of the Lyα forest flux. For each individual simulation, 100 000 skewers were drawn with random origin and direction, and the one-dimensional power spectrum computed at different redshifts. The final theoretical power spectrum is an average obtained from all the individual skewers, for any given model.

To account for non-standard dark radiation scenarios in $\mathcal{L}^{\rm Ly\alpha}$, we should extend the parameter space $\boldsymbol{\Theta}$ to include models with sterile neutrinos or more generic

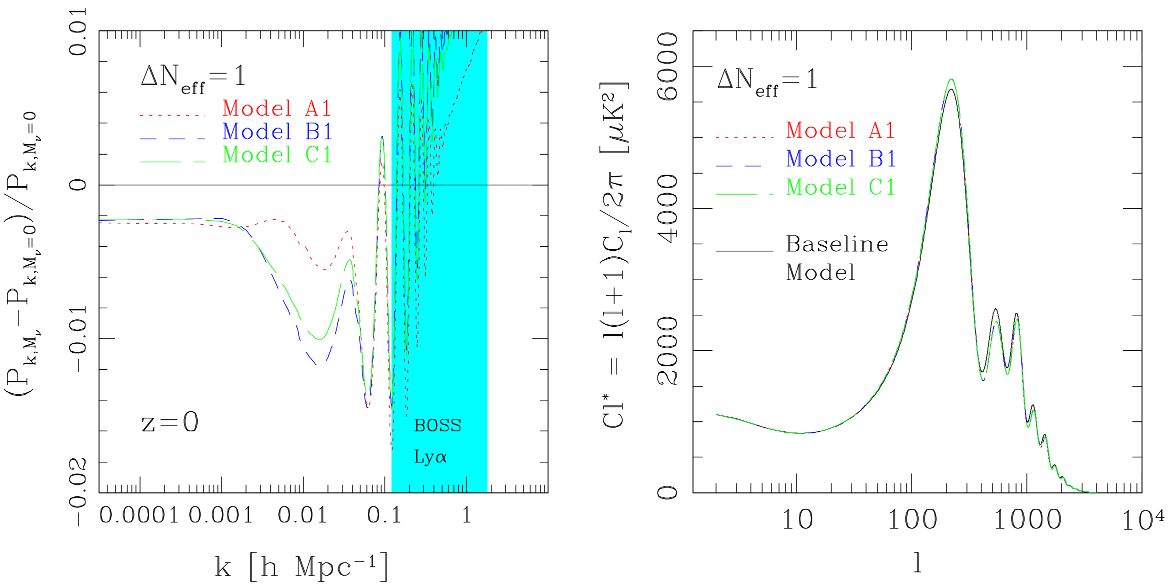

FIG. 1: Testing the accuracy of our analytic approximation to include non-standard dark radiation models. [Left] Linear matter power spectra for a series of models $\tilde{\mathcal{M}}$ having $\Delta N_{\rm eff} = 1$ at $z = 0$, normalized by the baseline model $\mathcal{M}$ with $N_{\rm eff} = 3.046$ and three active neutrinos of degenerate mass, when $M_\nu = 0.3$ eV. See the main text for more details. [Right] Corresponding CMB temperature power spectra for the same models. Both panels show small differences in the scale of BAO and CMB peaks, but they do not affect the Lyα likelihood.

relic radiation, where $N_{\rm eff}$ is different from the canonical reference value corresponding to three thermalized active neutrinos (i.e., $N_{\rm eff} = 3.046$). The Taylor expansion of the one-dimensional Lyα flux power spectrum will then include further terms, due to the presence of a non-standard $N_{\rm eff}$ value, but the logic leading to the construction of $\mathcal{L}^{\rm Ly\alpha}$ and the subsequent analysis remain essentially the same. Therefore, in principle we just require additional cosmological hydrodynamical simulations to map out the extended parameter space and evaluate extra cross-derivative terms in the Taylor expansion. However, this computationally expensive procedure can be avoided with the following strategy. Consider two models $\mathcal{M}$ and $\tilde{\mathcal{M}}$ defined by N cosmological parameters $\boldsymbol{\alpha}$ and $\tilde{\boldsymbol{\alpha}}$, which also include massive neutrinos. Model $\mathcal{M}$ is the reference model with the standard value of $N_{\rm eff} = 3.046$, while model $\tilde{\mathcal{M}}$ has $\tilde{N}_{\rm eff} = N_{\rm eff} + \Delta N_{\rm eff}$, with $\Delta N_{\rm eff} \neq 0$. In particular, we restrict our analysis to the case of three species of degenerate massive neutrinos and assume individual neutrino masses $m_{\nu,\rm i} < 0.6$ eV, so that they are fully relativistic at the redshift of equality $z_{\rm eq}$. The basic idea is to map the model $\mathcal{M}$ into a different model $\tilde{\mathcal{M}}$ with $N_{\rm eff} \neq 3.046$, which produces the same (or almost the same) total matter linear power spectrum as $\mathcal{M}$. If the two models are characterized by the same linear matter power spectrum, they will also have nearly identical nonlinear matter and flux power spectra. Hence, one can simply rely on linear theory and on simulations with standard $N_{\rm eff}$ to specify more exotic dark radiation scenarios. It is easy to prove that the previous condition is realized if $\mathcal{M}$ and $\tilde{\mathcal{M}}$ have the same values of $z_{\rm eq}$, $\Omega_{\rm m}$, $\omega_{\rm b}/\omega_{\rm c}$ and f_ν, with $\Omega_{\rm m}$ the matter density, $\omega = \Omega h^2$, and $f_\nu = \omega_\nu/\omega_{\rm m}$ – where the labels m, b, c, ν stand for total matter, baryons, cold dark matter, and neutrinos – respectively. This is true up to small differences in the scale of BAO peaks, but the fact that the location of BAOs slightly differs in the two cases is unimportant for the Lyα likelihood. In particular, the condition on f_ν guarantees that both the small-scale suppression in the matter power spectrum and the small-scale linear growth factor are identical in $\mathcal{M}$ and $\tilde{\mathcal{M}}$. Based on these requirements, the following two models will have nearly the same total linear matter power spectrum:

$$\mathcal{M} = \{\omega_{\rm b}, \omega_{\rm c}, H_0, N_{\rm eff}, \omega_\nu\} \tag{3}$$

$$\begin{aligned}\tilde{\mathcal{M}} &= \{\tilde{\omega}_{\rm b}, \tilde{\omega}_{\rm c}, \tilde{H}_0, \tilde{N}_{\rm eff}, \tilde{\omega}_\nu\} \\ &= \{\eta^2\omega_{\rm b}, \eta^2\omega_{\rm c}, \eta H_0, N_{\rm eff} + \Delta N_{\rm eff}, \eta^2\omega_\nu\}\end{aligned} \tag{4}$$

with

$$\eta^2 = [1 + 0.2271(N_{\rm eff} + \Delta N_{\rm eff})]/[1 + 0.2271 N_{\rm eff}] \tag{5}$$

and $\tilde{M}_\nu = \tilde{M}_\nu^{\rm a} + \tilde{M}_\nu^{\rm s} = \eta^2 M_\nu$ – where in the last passage we distinguish between the active and sterile contributions to the total mass (if the sterile neutrino has non-zero mass), and $M_\nu = \sum m_\nu$. Figure 1 shows that the previous approximation is accurate within 1% in the regime of interest (i.e., BOSS Lyα forest region, shaded cyan area in the left panel), which is comparable with

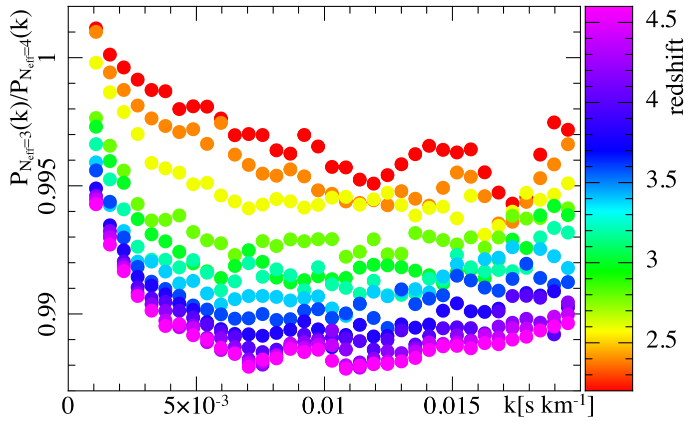

FIG. 2: Ratios of synthetic one-dimensional Lyα flux power spectra extracted from a baseline model $\mathcal{M}$ having three degenerate massive neutrinos and no extra relativistic degrees of freedom ($N_{\rm eff} = 3$, $M_\nu = 0.35$ eV), and from a non-standard dark radiation model $\tilde{\mathcal{M}}$ characterized by a massless sterile neutrino and three active neutrinos of degenerate mass ($\tilde{N}_{\rm eff} = 4$, $\tilde{M}_\nu = 0.4$ eV). The cosmological parameters of $\mathcal{M}$ and $\tilde{\mathcal{M}}$ are fixed according to (3) and (4). At any given redshift, indicated by different colors in the figure, deviations in the corresponding power spectra are all within 1% – comparable to those obtained from linear theory. Hence, our analytic approximation is also valid in the nonlinear regime.

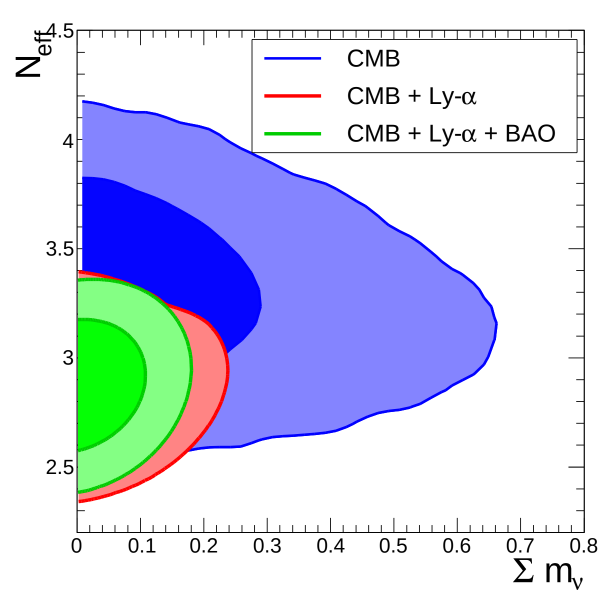

FIG. 3: Joint constraints on the number of effective neutrino species $N_{\rm eff}$ and the total neutrino mass $\sum m_\nu$, obtained from different cosmological probes. Red contours in the figure refer to the combination of CMB+Lyα data, while green contours include additional information from BAOs; in the first case we obtain $N_{\rm eff} = 2.91^{+0.21}_{-0.22}$ and $\sum m_\nu < 0.15$ eV, while in the second $N_{\rm eff} = 2.88 \pm 0.20$ and $\sum m_\nu < 0.14$ eV – all at 95% CL. Our results exclude the possibility of a sterile neutrino – thermalized with active neutrinos – at a significance of over 5 σ, favor the normal hierarchy scenario for the masses of the active neutrino species, and provide evidence for the CNB from $N_{\rm eff} \sim 3$ – as $N_{\rm eff} = 0$ is rejected at more than 14 σ.

our expected uncertainties from hydrodynamical simulations. Specifically, the left panel shows linear power spectra computed with CAMB [21] for different dark radiation models $\tilde{\mathcal{M}}$ having $\Delta N_{\rm eff} = 1$ at $z = 0$, normalized by the baseline model $\mathcal{M}$ which has $N_{\rm eff} = 3.046$ and assumes three active neutrinos of degenerate mass – when $M_\nu = 0.3$ eV. In particular, model A1 – characterized by a massless sterile neutrino thermalized with three active neutrinos of degenerate mass – is the main focus of this study, while in the other models the sterile neutrino is massive, thermalized, and shares the same mass as the three active species (B1), or has a different mass (C1); in the latter case, the mass fraction of the sterile neutrino is $(1 - \eta^{-2})$ of the total neutrino mass of the baseline model. The right panel shows the CMB power spectra for the same models, which are significantly different – unlike the linear matter power spectra. Note that at higher redshift and up to the time of radiation-to-matter equality, the difference between the various linear power spectra is as small as at $z = 0$. Our goal is to use this analytic approximation only in the Lyman-α likelihood; for the CMB and BAO scale likelihoods, we always assume the full exact models.

Results – The accuracy of our analytic approximation has also been tested in the nonlinear regime, by performing cosmological hydrodynamical simulations with non-standard $N_{\rm eff}$ values and verifying the robustness of our fitting procedure – along with the correct recovery of the nonlinear matter and Lyα flux power spectra. For example, we run a simulation based on a model $\tilde{\mathcal{M}}$ with $\tilde{N}_{\rm eff} = 4$ and $\tilde{M}_\nu = 0.4$ eV, where an additional massless sterile neutrino is assumed to be in thermal equilibrium with three degenerate active massive neutrinos; we also run the corresponding baseline model $\mathcal{M}$ having $N_{\rm eff} = 3$ and $M_\nu = \tilde{M}_\nu/\eta^2 = 0.35$ eV – where the cosmological parameters are determined according to (3) and (4). In particular, Figure 2 shows the ratios of synthetic Lyα forest flux power spectra extracted at different redshifts from those two models: even in the nonlinear regime, we find that deviations in the power spectra of $\tilde{\mathcal{M}}$ and $\mathcal{M}$ are within 1% for all the z-intervals of interest.

Having fully validated our analytic approximation, we implemented the extension to dark radiation models in the procedure applied in [5] and previously described. The global likelihood $\mathcal{L}$ obtained with this method is finally interpreted in the context of the frequentist approach [18]. This is done by minimizing the quantity $\chi^2(\boldsymbol{X}, \boldsymbol{\sigma}|\boldsymbol{\Theta}) = -2\ln[\mathcal{L}(\boldsymbol{X}, \boldsymbol{\sigma}|\boldsymbol{\Theta})]$ for data measurements $\boldsymbol{X}$ with experimental Gaussian errors $\boldsymbol{\sigma}$. In particular, first we compute the global minimum χ^2_0, leaving all the N cosmological parameters free. We then set confidence levels (CL) on a chosen parameter $\alpha_{\rm i}$ by performing the minimization for a series of fixed values of

Parameter	CMB+Lyα	CMB+Lyα+BAO
$n_{\rm s}$	$0.950^{+0.007}_{-0.008}$	0.949 ± 0.007
H_0 [km/s/Mpc]	67.0 ± 1.3	66.8 ± 1.3
$\sum m_\nu$ [eV]	< 0.15 (95%)	< 0.14 (95%)
σ_8	$0.831^{+0.013}_{-0.015}$	$0.834^{+0.015}_{-0.020}$
$\Omega_{\rm m}$	0.308 ± 0.015	0.311 ± 0.009
$N_{\rm eff}$	$2.91^{+0.21}_{-0.22}$	2.88 ± 0.20

TABLE I: Values of the main cosmological parameters obtained from a frequentist analysis of the likelihood $\mathcal{L}$, as explained in the main text, for the two combinations of datasets considered in this work – CMB+Lyα or CMB+Lyα+BAO.

$\alpha_{\rm i}$ – thus with $N-1$ degrees of freedom; the difference between χ^2_0 and the new minimum allows us to compute the CL on $\alpha_{\rm i}$. This technique is readily extended to higher dimensions, in order to derive joint constraints on two (or more) cosmological parameters. Figure 3 summarizes the main results of our fitting procedure for the values of $N_{\rm eff}$ and $\sum m_\nu$, derived by combining CMB (Planck+ACT+SPT+WMAP polarization; blue contours) with Lyα forest data (red contours), or by further adding BAO information (green contours). Specifically, we obtain $N_{\rm eff} = 2.91^{+0.21}_{-0.22}$ (95% CL) and $\sum m_\nu < 0.15$ eV (95% CL) in the first case, and $N_{\rm eff} = 2.88 \pm 0.20$ (95% CL) and $\sum m_\nu < 0.14$ eV (95% CL) in the second. Table I reports the final results of the fits for all the main cosmological parameters ($\boldsymbol{\alpha}$), in addition to $N_{\rm eff}$ and $\sum m_\nu$, for the two combinations of datasets considered (i.e., CMB+Lyα or CMB+Lyα+BAO).

Simultaneous constraints on $N_{\rm eff}$ and $\sum m_\nu$ are interesting, since extra relics could coexist with massive neutrinos or could themselves have a mass in the eV range. From CMB measurements alone, these two parameters do not show significant correlations because their physical effects can be resolved individually, while $N_{\rm eff}$ and $\sum m_\nu$ may be partially degenerate when considering LSS tracers (actually, in the range of validity of the analytic approximation that we use for Lyα data, these two parameters are totally degenerate). However, the most constraining power comes from the combination of CMB and LSS, because distinct cosmological probes have different and independent systematic errors, and contrasting directions of degeneracy in parameter space. This is particularly true for the Lyα forest, which reduces the uncertainties on cosmological parameters quite significantly when combined with CMB measurements. With respect to the total neutrino mass, the ability to place a strong upper limit ultimately derives from the fact that the distinctive scale- and redshift-dependence suppression of power in the matter and Lyα flux power spectrum caused by neutrinos cannot be mimicked by a combination of other parameters, and is not fully degenerate. In the case of $N_{\rm eff}$, most of the information comes from precise measurements of the photon diffusion scale relative to the sound horizon scale (hence from the CMB), but the combination of other parameters in the Lyα likelihood and very different directions of degeneracy in parameter space contribute to tighter limits. For example, we tested this by completely removing the dependence on $N_{\rm eff}$ in $\mathcal{L}^{Ly\alpha}$, and found that our final limits on $N_{\rm eff}$ varied only marginally – confirming that most of the constraining power on the number of effective neutrino species indeed resides in the CMB, although some additional – albeit small – information is also contained in the Lyα forest. Therefore, we would expect that the combination of CMB+Lyα will always perform better than the CMB alone, and if combined with upcoming Planck (2014) data the results presented here will be tighter. In essence, the key is the synergy of the CMB with a high-redshift tracer having different systematics and probing different directions in parameter space. We also note that there is no significant correlation between $N_{\rm eff}$ and $\sum m_\nu$ in the CMB+Lyα contours, and therefore our upper limits on the total neutrino mass obtained from a joint analysis are consistent with [5].

Joint constraints on the number of effective neutrino species and the total neutrino mass are also in general model-dependent. In this study, to derive our limits on $N_{\rm eff}$ and $\sum m_\nu$ we assumed that the three active neutrinos share a mass of $\sum m_\nu/3$, where $m_{\nu,{\rm i}} < 0.6$ eV, and may coexist with massless extra species contributing to $N_{\rm eff}$ as $\Delta N_{\rm eff}$. Based on these assumptions, the main conclusions of our analysis are as follows: (1) the possibility of a sterile neutrino thermalized with active neutrinos – or more generally of any decoupled relativistic relic with $\Delta N_{\rm eff} \simeq 1$ – is ruled out at a significance of over 5 σ, the strongest bound to date; (2) as in [5], our results on $\sum m_\nu$ favor the normal hierarchy scenario for the masses of the active neutrino species, and represent the strongest upper bound to date on the total neutrino mass; (3) by rejecting $N_{\rm eff} = 0$ at more than 14 σ, our constraints provide the strongest evidence for the CNB from $N_{\rm eff} \sim 3$. These results have several important implications in particle physics and cosmology. In particular, the effective number of neutrino-like relativistic degrees of freedom is found compatible with the canonical value of 3.046 at high-confidence, suggesting that the minimal ΛCDM model – along with its thermal history – is strongly favored over extensions with non-standard neutrino properties or with extra-light degrees of freedom, and the measured energy density is composed of standard model neutrinos. Hence, no new neutrino physics nor new particles are required, and the theoretical assumptions going into the standard cosmology theory are correct. In addition, along with [5], our bounds on $\sum m_\nu$ favor the normal hierarchy scenario, and suggest interesting complementarity with future particle physics direct measurements of the effective electron neutrino mass [4]. Finally, our conclusions on the CNB will nicely complement upcoming results from Planck, which is expected to detect the free-streaming nature of the species responsible for $N_{\rm eff} \sim 3$ with high significance. We expect that our constraints on $N_{\rm eff}$ will be improved by a factor of 2 by including eBOSS measurements, while DESI should improve these constraints even further [22].

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